WAVES AND TURBULENCE IN STELLAR WINDS ACROSS THE H-R DIAGRAM

NASA Grant NNG04GE77G

ANNUAL REPORT

For the period 1 March 2004 to 28 February 2005

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January 2005

Prepared for
National Aeronautics and Space Administration
Washington, DC 20546

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1. Required Information

Type of report	**Annual Progress Report** (Year 1 of 5)
Title of NASA SR&T grant	Waves & Turbulence in Stellar Winds across the H–R Diagram
Name of the principal investigator ..	Dr. Steven R. Cranmer
Period covered by the report	March 1, 2004 to February 28, 2005
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Grant number	NNG04GE77G

2. Scientific Accomplishments during the Report Period

During the first year of this project, the PI began work in several areas that are expected to yield a substantial increase in our understanding of how and why stars form winds and disks. The approach outlined in the original proposal comprised four complementary pieces (cool and hot stars; observations and theory for each), and the accomplishments in this report period are thus divided into these 4 categories:

1. *Cool Star Winds: Observations.* I have begun a collaboration with A. Dupree and E. Avrett at SAO to analyze and model the spectroscopic signatures of outflows in late-type dwarfs, giants, and supergiants. Specifically, we are attempting to understand the detailed formation mechanisms of chromospheric (e.g., He I 10830 Å) and transition region (e.g., C III 977 Å) lines, which in some stars exhibit blueshifted absorption that indicates flow speeds up to 100–200 km/s. The growing database of spectra includes space-based data from *FUSE* as well as ground-based data from CSHELL/IRTF, FTS/CFHT, SOFIN/NOT, NIRSPEC/KECK, PHOENIX/GEMINI, and ICS/SUBURU (see, e.g., Dupree et al. 2004a, astro–ph/0412539; Dupree 2004b, IAU Symp. 219, in press). Preliminary surveys of these data indicate that winds of luminous stars in the so-called "hybrid-chromosphere" range may be accelerated to supersonic speeds in their cool chromospheres.

2. *Cool Star Winds: Theory.* After considering the proposed idea to adapt an existing solar wind MHD code to the more general application of late-type stars, it became clear that the best option would be to write a new program from scratch. Thus, I have written the ZEPHYR code that uses a newly developed relaxation technique to solve for the steady-state 1D photosphere, chromosphere, corona, and wind conditions for a given star. Currently in final beta-testing mode, ZEPHYR includes chromospheric shock heating, Alfvén wave pressure and turbulent heating terms (motivated by current solar wind models), an up-to-date description of radiative heating and cooling, and a realistic transition from classical (Spitzer-Härm) to non-classical (saturated) heat conduction.

   The ZEPHYR code will be used to produce grids of model atmospheres/winds that will then be folded through either: (1) the Avrett & Loeser PANDORA spectral synthesis code, or (2) my multidimensional SEI radiative transfer code; in order to compare with observed spectra (see item 1 above). In addition to model grids with freely varied parameters, I am developing model grids where the acoustic and Alfvén wave fluxes are given by published predictions of turbulent convection models (e.g., Musielak et al. 2002, *A&A*, 386, 606). ZEPHYR can thus be used to test various hypotheses concerning how cool-star winds are accelerated. One speculative idea is that if the onset of coronal heating is "delayed" by several scale heights, the Alfvén wave pressure can build to the point of accelerating a cool wind past the sonic point.

   As a part of a NASA SR&T program that is ending in early 2005, I have also been developing

BOREAS, a Monte Carlo solar wind code that computes the non-Maxwellian velocity distributions of protons in the gradual transition from the collisionally-coupled corona to the collisionless outer wind. This code may also be adapted to cool-star winds if the results from ZEPHYR indicate that collisionless effects would be important to include.

3. *Hot Star Winds: Observations.* The bulk of my work in this area during the first year of this program was devoted to identifying the threshold rotation rates of Be stars for the formation of dense "decretion disks." The impact of pulsations and waves on these disks cannot be identified quantitatively until the exact range of rotation speeds needed to form disks can be identified. Past work has either underestimated or ignored the effects of *gravity darkening* on the formation of photospheric absorption lines (from which we measure the projected rotation rate $V_{\rm rot} \sin i$). I have obtained an extensive observational database (made available by R. V. Yudin) of the properties of over 450 Be stars and performed a statistical "forward modeling" analysis to see what distributions of $V_{\rm rot}$ would yield the observed distributions of $V_{\rm rot} \sin i$. (A paper on these results is about 50% completed as of December 2004, and will be submitted for publication in the first couple of months of 2005.)

   I have also begun assembling data from the rapidly growing literature on spectroscopic, polarimetric, and interferometric determinations of Be-star inclinations, disk densities, and pulsation properties. For example, an empirical comparison between the empirically determined "inner" disk density and the photospheric density provides a firm constraint on the radial extent of the region over which angular momentum must be added to form the Keplerian disk.

4. *Hot Star Winds: Theory.* The first theoretical work I performed under this program was to continue the analytic wave study that was begun in my 1996 Ph.D. dissertation. I found that the presence of a subsonic wind in the lower atmosphere of an early-type star eliminates the phenomenon of evanescence for radially propagating acoustic-gravity waves. Thus, low-order p-mode and g-mode pulsations (which would otherwise be evanescent in a static atmosphere) can "leak" into the wind and produce observable variations in spectral lines formed at large distances from the star. I updated the code that solves the dispersion relation for such waves and performed a preliminary study of the ability of these waves to produce second-order angular momentum transport (e.g., Saio 1994, IAU Symp. 162, 287). The results of this study were negative (i.e., realistic pulsation amplitudes would produce negligible "disk spin-up") but the more general results of wave leakage will be explored further in Year 2.

   Also, in collaboration with A. van Ballegooijen, I have begun a study of specific physical processes that can supply angular momentum to Be-star disks. These processes include: (1) meridional radiative forces above the photosphere that may transport energy and momentum in ways similar to Hadley cells in the Earth's atmosphere; and (2) radiative instabilities that, when amplified to nonlinear strengths, can also transport energy and momentum as in mixing-length convection theories. As outlined in my original proposal, these processes are all directly or indirectly related to pulsations and waves in the atmospheres of these stars.

3. Comparison of Accomplishments with Proposed Goals

In the original proposal, my Year 1 plan of work spelled out 75% of the time for observational research and 25% for theory. It has evolved into more of a 50/50 split between these highly complementary areas. The initial development of the ZEPHYR code was a mainly theoretical effort, but it will applied as a tool for analyzing observations in Year 2. In response to the reviewer's comment that the proposed cool-star "observational" research would have been limited to a literature search, I have shifted its focus to the direct analysis of data in collaboration with A. Dupree and E. Avrett. (The collation of dynamical wind properties from the literature will still be performed, but at a lower priority.)

It should be noted that Year 1 was funded at a 66% level because of an ongoing SR&T grant for the PI that will end in May 2005. All things considered, though, the accomplishments presented above correspond closely to the proposed work plan and the details of technical approach and methodology presented in the proposal.

4. Publications and Conference Presentations

Being my first year of stellar research since 1996, a portion of my time during the early part of Year 1 was devoted to "getting back up to speed" in these fields. Thus, there have not yet been any publications submitted to refereed journals as of December 2004. The hot-star theory paper on Be-star threshold rotation rates is about 50% completed and will be submitted to *Ap.J.* in the first few months of 2005. A paper describing initial results of the ZEPHYR code will be prepared during the first half of 2005. A paper describing the leakage of pulsational energy into the winds of hot stars will be prepared during the second half of 2005.

My transition from the solar wind to stellar winds was exemplified by the fact that I was invited to give a 30-minute review talk on "New Insights into Solar Wind Physics from *SOHO*" at the *13th Cambridge Workshop on Cool Stars, Stellar Systems, and the Sun* in Hamburg, Germany, July 5–9, 2004 (see proceedings paper at astro–ph/0409260). My talk was the only solar wind talk at the meeting, and it was an ideal opportunity to assess the current state of cool-star wind research. Attending this meeting was extremely helpful in the development of modeling ideas for cool-star winds, and for the identification of the key unknowns at the forefront of the field. As a part of my continuing solar work I also attended the AAS/SPD meeting in Denver (May 2004) and gave an invited talk at the *SOHO*–15 workshop in St. Andrews, Scotland (September 2004).

Finally, as a part of an informal collaboration with the *Stellar Imager* Vision Mission team at SAO (headed by M. Karovska), I wrote a 10-page set of notes on potential hot/massive star "areas of interest" for this future mission. These notes surveyed current issues in the sub-fields of hot-star rotation, Be-star disks, the photospheric connection between stellar variability and wind variability, wind-collision shocks in close binaries, Wolf-Rayet winds, LBV winds, and hot-star asteroseismology. These notes are available at: http://cfa-www.harvard.edu/~scranmer/cranmer_unpub.html

5. Statement of Work for the Next Report Period

The Work Plan for the following year (March 1, 2005 to February 28, 2006) is expected to follow closely the "Year 2" description in the original proposal. For cool-star winds, the ZEPHYR code will be optimized and run for a large number of specific stars. The empirically constrained wave fluxes (required to produce agreement with observed spectral features) will be compared to theoretical predictions. For hot-star winds, the leakage of pulsational energy into the outflowing circumstellar gas will be modeled both analytically and numerically. Be-star observations will be further processed to produce firm empirical constraints on the rate and spatial extent of the angular momentum supply to the disk. All results will be published in a timely fashion.

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